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Abstract

Intermodal transportation has sustained a promising growth rate over the past two decades and continues to be one of the rapidly growing segments of the transportation industry. Intermodal transportation is increasingly being used to move hazardous materials, and most of the studies underline the irreversible nature of this trend. In this paper, we make a first attempt to develop an understanding of the risk-cost-time trade-offs that underlie decisions pertaining to dangerous goods shipments via a rail-truck intermodal transportation system. A realistic case study that focuses on transportation of both dangerous goods and regular freight among one 100 shipper-receiver pairs in Canada is developed, and an intelligent enumeration algorithm to solve the problem is presented.

Key words: intermodal transportation, dangerous goods, population exposure risk, enumeration technique, trade-offs.

Résumé

Le transport intermodal a maintenu un taux de croissance au cours des deux dernières décennies et continue d'être un des segments croissants de l'industrie du transport. Le transport intermodal est utilisé de plus en plus pour déplacer des matériels dangereux, et la plupart des études soulignent la nature irréversible de cette tendance. Dans cet article, nous faisons une première tentative pour développer une compréhension du risque/coût sur les échanges de temps à la base des décisions qui se rapportent aux chargements d'articles dangereux via un système de transport intermodal par train-camion. Une étude de cas sur le transport d'articles dangereux et réguliers comportant une centaine de paires d'expéditeurs-récepteurs dans le Canada est développée et un algorithme d'énumération intelligent pour résoudre le problème est présenté.

Mots clés : transport intermodal, matières dangereuses, risque d'exposition, énumération technique, échanges.

1. Introduction

Rail-truck intermodal transportation (IM) combines accessibility advantage of road networks with scale economies associated with railroads in moving shipments. The main attractiveness of IM for shippers is its reliability in terms of on-time delivery as well as the significant reduction in delivery times in comparison with traditional trains. Perhaps due to these competitive advantages, IM has experienced an impressive growth over the past two decades, and continues to be one of the rapidly expanding segments of the transportation industry. Furthermore, intermodal shipments constitute the fastest growing activity for railroad companies and they are slated to overtake coal as the largest source of revenue (Logistics Management, 2004). The phenomenal growth of intermodal transportation has been attributed to the competitive pressures on global supply chains (Szyliowicz, 2003), the increasing demand for new service patterns driven by ocean carriers (Stone, 1997), as well as the globalization of industry (Stone, 1999; Rondinelli and Berry, 2000).

IM is increasingly being used for hazardous materials (hazmats) shipments that are potentially harmful for human health and the environment. For example, the Bureau of Transportation Statistics estimated that in 1997 over one and half million tons of hazmats were shipped across the U.S. intermodal transportation system (U.S. DoT, 1997). This statistic is already qualified as an underestimate by the 2002 Commodity Flow Survey (U.S. DoT, 2004). With regards to the future, the U.S. Chemical Manufacturers Association estimates that the total volume of hazmats shipped by 2020 will be 5.1 billion tons, which according to the U.S. Department of Transportation (2000) will be increasingly carried via intermodal transportation channels.

Despite the increasing significance of IM in carrying hazmats, Erkut et al. (2005) identified –through a comprehensive review of the literature on hazmat logistics- that IM is an area that has not been studied in this domain. In this paper, we make a first attempt to develop a solid understanding of the trade-offs that underlie the decisions pertaining to dangerous goods shipments via IM. To this end, we build a realistic case study that focuses on transportation of hazmats across Canada (i.e., from Quebec to British Columbia) among one hundred shipper-receiver pairs via IM network of Canadian Pacific Rail Company (CPR). Since there is a single pair of intermodal rail terminals (IMRT) in the illustrative case study –located at Montreal and Vancouver, the arising problem lends itself to solution via an intelligent enumeration algorithm. Therefore, our contribution is a detailed analysis of the risk-cost-time trade-offs that define the problem (which has not been studied before) rather than the development of a solution algorithm for the most general case.

Excellent reviews of the academic literature on intermodal transportation can be found in Macharis and Bontekoning (2003), Bontekoning et al. (2004), and Crainic and Kim (2005). Here, we focus on the studies pertaining to IM and provide an overview. A detailed description of IM systems will be provided in the next Section. In brief, IM involves inbound drayage of the intermodal container unit via truck to the origin IMRT, transfer of the container onto the intermodal railcar, rail-haul between the IMRT pair, transfer of the container onto the truck at the destination IMRT, and finally, outbound drayage to the receiver via truck. According to Morlok and Spasovic (1995) and Gooley (2001), trucking constitutes the weakest links of the

intermodal chain, and is viewed as an opportunity for significant service improvement and cost reductions. The planning and decision-making regarding rail-haul can be strategic, tactical or operational in nature. The works with strategic implications typically focus on network and service design, freight terminal location, and equipment design (Richardson, 2002; Wiegmans et al., 1999; Priemus, 1999; Bontekoning, 2000; Barton et al., 1999; Arnold et al., 2003; Ballis and Golias, 2004; Southworth and Peterson, 2000; Rizzoli et al., 2002; Evers, 1994). The prevailing studies adopting an intermediate time horizon are on train scheduling and container routing (Newman and Yano, 2000), intermodal container routing (Bookbinder and Fox, 1998), planning operations for an intermodal rail-truck service (Nozick and Morlok, 1997), minimum cost intermodal routings (Barnhart and Ratliff, 1993), and on bundling operations (Trip and Bontekoning, 2002; Jourquin et al., 1999; Janic et al., 1999). The work of Powell and Carvalho (1998) is operational in nature. To the best of our knowledge, there is not a single refereed publication involving intermodal transportation of hazmats – which is confirmed by Erkut et al. (2005). This paper aims at making a step toward filling this important gap in the literature.

The remainder of the paper is organized as follows: Section 2 describes a typical rail-truck intermodal transportation system. Section 3 presents an instance of the problem in Canada, which is used in the following sections as an illustrative case. Section 4 describes an evaluative framework, whereas the underlying trade-offs in IM transportation of hazmats are analyzed in Section 5 -within the context of the case. We conclude the paper by outlining future research directions in Section 6.

2. Rail-Truck Intermodal Transportation System

In this section we describe a typical IM network, which is depicted in figure 1. An intermodal unit (container and/or trailer) to be sent from shipper *(i)* to receiver *(l)* is first transported by truck to IMRT *(j)*, where it is transshipped from truck onto a train. The train provides the transport until IMRT *(k)*, where the container is transshipped back on a truck on its way to the receiver *(l)*. Intermodal trains, unlike traditional freight trains, operate on a *fixed-schedule*, and are usually quite punctual (Nozick and Morlok, 1997), therefore such trains often operate non-stop between a pair of IMRTs, although infrequent stops and

transfer of railcars among trains are also possible. Intermodal trains are quite distinct from the traditional rail services which have been the subject of much modeling in the last two decades (see Assad, 1980; Cordeau et al., 1998). The need to match (i) the intermodal unit with the railcar; and, (ii) the shipment with the levels of services provided by the train is the noteworthy difference. Nonetheless the inbound and outbound drayage provided by trucks is the most expensive activity in IM, and accounts for 40% of the total intermodal transport cost (Bontekoning et al., 2004).

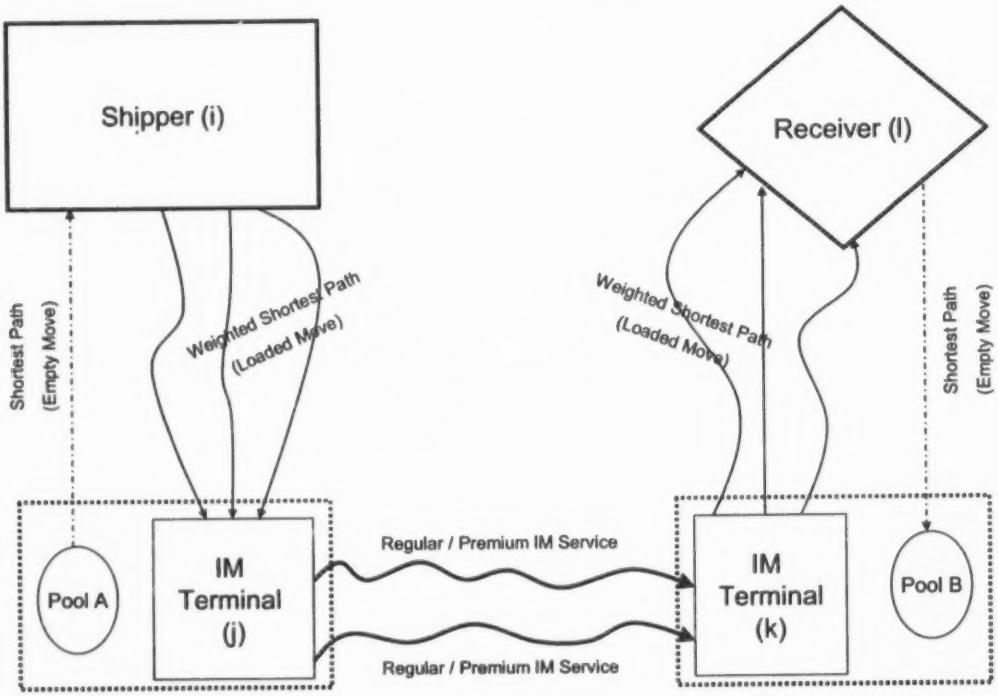

Figure 1: A Rail-Truck Intermodal Network

Figure 2 shows an intermodal (ISO or IMO) container for hazardous cargo, a special truck-trailer to move such containers, and the crane operations at an IMRT. The tractor-trailer pools (*'A'* and *'B'* in figure 1) are usually maintained in the vicinity of the IMRT, and an empty unit is dispatched when requested by a shipper. Of course, railroad companies offer different plans, whereby the intermodal unit (also referred to as container in this paper) can belong to the shipper or the railroad company. For example CPR offers six

different plans in Canada: ramp-to-ramp; door-to-door; door-to-ramp; ramp-to-door; door-to-door (container belongs to the shipper); and, ramp-to-door (container belongs to the shipper) (Calluri, 2004).

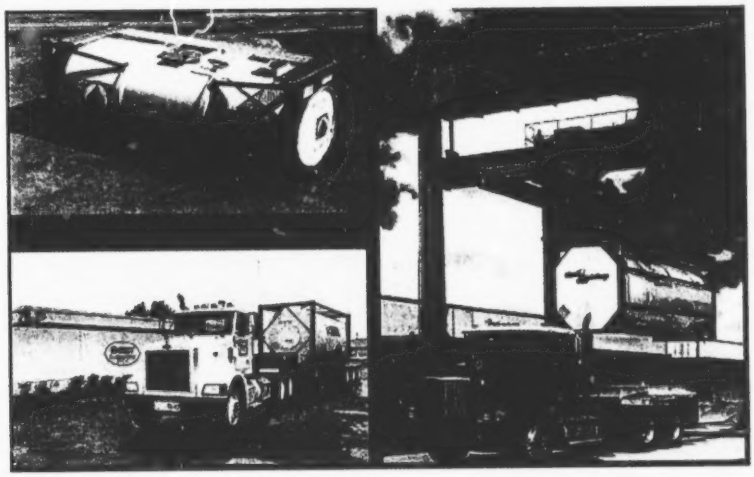

Figure 2: Intermodal transportation of hazmats

In the context of IM, each shipment order has a delivery time requirement. Using the notations in figure 1, shipper *(i)* would request intermodal units based on the shipment order from the nearest IMRT. Naturally this request may also include certain ISO containers for hazmats. On receiving the request, the IMRT will dispatch the specified containers from the pool, which starts *inbound drayage*. Obviously the drivers will take the shortest route from Pool-*A* to shipper *(i)*. On reaching shipper *(i)*, a driver has two options: either to un-hitch the container and leave, or to stay-with the container. Once the container is ready to leave shipper *(i)*, the truck driver brings it to the IMRT for the rail-haul. If the intermodal unit contains hazardous cargo, the driver may choose a route that avoids public and environmental risk on way to IMRT. Using the cranes the containers are placed on the flat railcars of the designated intermodal train (figure 2 shows a gantry crane).

At the origin IMRT *(j)*, the routing of rail-haul is determined. Given the sparse railroad network and even sparser IMRT network in North America, often there is a single preferred routing to each destination but there will be time-of-departure options for all but the highest class of service. Following arrival to IMRT *(k)* the container needs to be delivered to the receiver *(l)* within the delivery time stipulated by the shipment order. Again, in the event that the cargo is potentially hazardous the truck may be routed so as to minimize

transport risk, which is not a concern for the empty truck on its return trip to Pool B. It is important to point out that customer service is the underpinning of IM operations, wherein delivery reliability distinguishes IM from conventional railroad transportation.

3. An Illustrative Case Study

It is evident from the literature overview provided in the Introduction that this paper constitutes the first step towards the development of an analytical framework for decision making in IM. This requires a solid understanding of the trade-offs underlying the problem, which we aim to articulate in this paper. To this end, we develop and analyze a realistic problem instance based on IM shipments across Canada by CPR - one of the two major railroad companies. The illustrative case is developed using publicly available data at the company's web site (www.cpr.ca), which is complemented by a detailed interview with one of it's staff in charge of IM (Calluri, 2004). Information pertaining to the existing railroad and road networks, location of the Montreal and Vancouver IMRTs as well as the population zones is represented via a geographical information system (GIS) model (ArcView, www.esri.com). The case data outlined in this section constitutes the basis of our analyses in the remainder of this paper.

In Canada, the westbound traffic volume via IM is significantly larger than that of the eastbound traffic (Calluri, 2004). Therefore, the case focuses on IM shipments from Quebec to British Columbia that contain hazardous as well as regular freight. Although the IM infrastructure and population data used in this case are accurate, we had to resort to hypothetical data pertaining to shipment orders because demand information is considered confidential by CPR. The randomly generated demand between origin-destination pairs range from 5 to 23 containers, while the number of containers with hazardous cargo vary from 2 to 11. A total of 1,036 container shipments are to be planned among 100 origin-destination pairs, where each shipment needs to be made within the delivery time stipulated in the order. Clearly, the analyses procedures presented in sections 4 and 5 are not dependent on these demand figures. CPR offers a door-to-door service plan with their equipment, which we adopt in this paper.

We assume that there are ten shippers in Quebec, distributed around Montreal, and each has to fulfill (hazmat and non-hazmat) orders of ten customers in British Columbia. The ten shippers are at *Repentigny*, *Boucherville*, *Saint Hubert*, *Brossard*, *Chateauguay*, *Beaconsfield*, *Kirkland*, *Saint-Eustache*, *Sainte-Therese*, and *Laval* (see Figure 3). The IMRT in *Lachine* municipality, on the Island of Montreal, is the only intermodal terminal available to these ten shippers. Furthermore, we assume that these shipments are directed to the Delta Port in *Vancouver*, British Columbia (see Figure 4). The ten receivers are: *Kelowna*, *Kamloops*, *Burnaby*, *Surrey*, *Richmond*, *Haney*, *Coquitlam*, *Forest Hills*, *Prince George*, and *Prince Rupert* (for the six receivers closest to Vancouver, see Figure 5). We assume that the truck driver stays on-site during loading and unloading at the shipper and receiver locations.

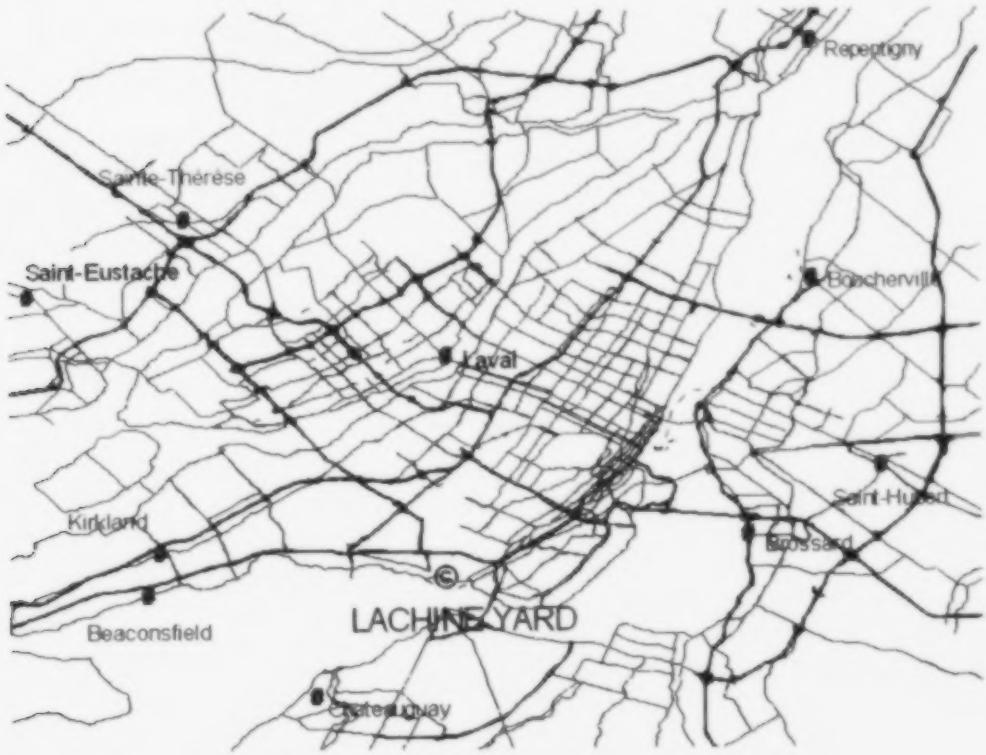

Figure 3: The Shippers and Lachine Intermodal Yard

Each shipper is linked to Lachine IMRT through the road network. The thicker links in Figure 3 represent the expressways, whereas the thinner links depicts roads of other types. Among the multiplicity of available

routes, it is natural for a truck driver to take the shortest path between the shipper and the IMRT as long as the cargo not hazardous.

Figure 4 depicts the two intermodal train routes between Lachine yard and Delta Port. Since the intermodal infrastructure is sparse in North America it is not plausible to have a large number of intermodal routes among an IMRT pair. We refer to the route passing through Edmonton (and bypassing Calgary) as the *North* route and the one passing through Calgary as the *South* route. On both routes there are two types of IM services: a *regular* service (R-IM) with a stop at Edmonton and Calgary respectively, to pick-up and drop-off traffic; and a *premium* service (P-IM) that is non-stop and faster but more expensive. We assume that all the parties strive for just-in-time management and hence the waiting times prior to loading, unloading and transshipment activities along the IM chain are negligible.

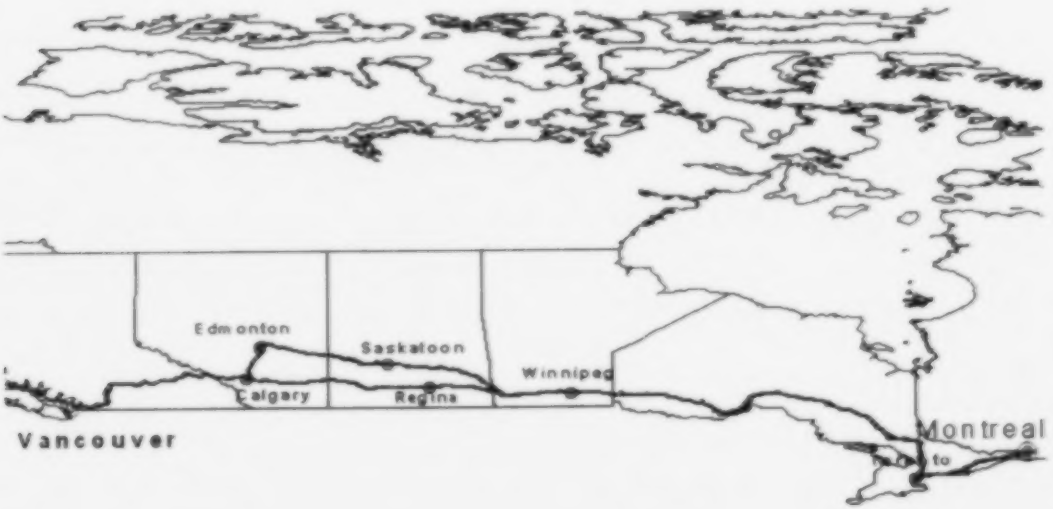

Figure 4: Intermodal Train Routes between Montreal and Vancouver

The final component of the case data is the required delivery times that elapse between the placement of each order and its delivery to the receiver. That is, the total delivery time (i.e., the sum of drayage, loading/unloading, and rail-haul) should satisfy the receiver's requirement. We assume that the receivers at *Kelowna* and *Kamloops* want to receive their orders within 5 days (120 hrs) from the time an order has been placed. Receivers in and around Vancouver (*Burnaby*, *Surrey*, *Richmond*, *Haney*, *Forest Hills* and

Coquitlam) have specified 4.5 days (108 hours) as the deadline. The two furthest points, *Prince George* and *Prince Rupert*, have specified 6 days for delivery

Based on the case data outlined in this section, we can now embark on an analysis of the IM routing options with respect to total cost, population exposure to hazmats as well as delivery time feasibility. In the next section an intelligent enumeration scheme, which takes advantage of the presence of a single IMRT pair in this case, is presented. This will be followed by a section that highlights the nature of the trade-offs among the cost, risk and time attributes of intermodal shipments of dangerous goods.

Figure 5: The Receivers and Delta Port Intermodal Yard

4. The Assessment of an Intermodal Shipment

In this section we present a scheme to assess an intermodal shipment that involves hazmats. Our approach is based on the three components of each such shipment i.e., inbound drayage, rail-haul and outbound drayage. Since the origin and destination of the rail-haul are pre-specified the assessment problem is amenable to solution by an enumeration-based procedure. Although, we have conducted the complete evaluation of all the 100 shipments in the case, for the sake of brevity we will highlight the *Repentigny-Kelowna* shipment. We make the following assumptions during assessment: First, the request for empty

containers is generated immediately on receiving an order from the receiver. Second, the shippers are aware of the departure times of the intermodal trains and resulting time by which shipments should be ready in order to make to a particular train. Third, a just-in-time approach is being incorporated whereby relevant activities are performed as soon as a container reaches the concerned location, and hence there is no waiting. Fourth, there is sufficient capacity and enough equipment at each stage of the intermodal chain, which implies no congestion.

Paths	*1*	*2*	*3*	*4*
Time(hrs.)	2.08	2.28	2.12	3.00
Distance (kms.)	83	91	85	120
Cost ($)	254	264	256	300
Population Exposure (people)	2959	2787	2557	1266

Table 1: Per Container Inbound Drayage to Repentigny

In Table 1, information pertaining to four of the paths between *Repentigny* and *Lachine* yard are presented. Path 1 indicates using the shortest path for both segments of inbound drayage. Path 2 through Path 4, imply taking the shortest path to the shipper, and then a different route to get back to the IMRT. Each path has four attributes: *time*, *distance*, *cost* and *risk*. In general, in Canada trucks can travel at a maximum speed of 50 km/hr in the city, but due to lights and traffic an average speed of 40 km/hr is assumed in this case study, and hence the travel time on the first path will be 2.1 hrs. Normally drayage is charged in terms of the amount of time the crew (driver-truck) is engaged, and at a very conservative estimate of $50/hr, the crew-cost-fuel for the transportation part is $104. Furthermore it is estimated that it will take approximately two hours to load a container at the shippers' site and an hour to unload it at the IM yard, for a combined crew cost of $150. Hence a container using Path 1 can be moved to the IM yard for $254, and similarly for other paths.

We use *population exposure* as the indicator of hazmat transport and handling risk, which is calculated using the Gaussian-plume-model based procedure developed in Verma and Verter (2005) and adopted in Verma et al. (2005). Based on the population census data, exposure levels are calculated using IDLH levels associated with propane. A danger circle centered at the point of handling will contain the exposed population center in the former instance, while an exposure band along the transportation corridors will

contain the population at risk in the latter instance. At the first shipper 1,557 people will be exposed due to the handling of a single container with hazardous cargo, and 53 such containers originating at this location will expose 82,521 people. Although the site exposure risk cannot be reduced without reneging on the orders, it is possible to implement a prudent routing approach that can reduce the network risk. It is not reasonable to take Path 1, the shortest path, to transport hazardous cargo since it goes through downtown Montreal thereby exposing more than double the number than does Path 4, the longest path which bypasses downtown Montreal. Unfortunately for our instance such a standard trade-off analysis will not suffice, and what we need is a risk-cost analysis driven by the element of *"time"*. Specifically, an evaluation that takes into consideration the two hard constraints: departure times of the schedule-based trains; and, delivery time specified by the receiver. It may be evident from Table 1 that by spending an extra $46 roughly 1,700 fewer people would be exposed for every hazardous container traveling on Path 4, but this also implies that the shipment has to be ready an hour earlier in order to make it to the same train. For all the 53 hazardous containers it means spending an extra $2,348, but exposing 89,729 fewer people. Generally it can be surmised that the increased cost and/or lower risk is acceptable only if the specified "*time*" element is not violated, and that each of the four paths in Table 1 is feasible if the shipments are readied at appropriate times.

On reaching the IMRT, cost will incur and risk will accrue due to the additional handling operations. While Barton et al. (1999) estimated $140 to be the cost of a lift at the IM yard we have assumed a rate of $150 to reflect current conditions. The IM yard in Lachine will handle containers from all the ten shippers, and will expose 837,666 people from handling 538 hazardous containers.

Now for the next link of the intermodal chain i.e., rail-haul, we first focus on the *North* route viz. through Edmonton. This route was measured at 2,920 miles in ArcView GIS. Average train speed, calculated using public information, of CPR in 2004 was 28.5 miles per hour, which was rounded up to 30 miles per hour for R-IM and the estimate for P-IM was 40 miles per hour. R-IM train will need a yard-to-yard time of 103 hours, including 6 hours for traffic swaps in Edmonton. On the other hand P-IM train, being both non-stop and faster, will cover the same distance in 73 hours.

Regular Intermodal Train Service: 97 hours.																				
INBOUND Drayage	Path 1					Path 2					Path 3					Path 4				
OUTBOUND Drayage	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Kelowna	5.03	4.93	4.93	4.94	4.94	5.04	4.94	4.94	4.94	4.95	5.03	4.94	4.94	4.94	4.94	5.07	4.97	4.97	4.97	4.96
Kamloops	4.96	4.92	4.93	4.93	4.92	4.96	4.93	4.94	4.94	4.93	4.96	4.92	4.93	4.93	4.93	4.99	4.96	4.97	4.97	4.96
Burnaby	4.64	4.64	4.64	4.65		4.65	4.65	4.65	4.66		4.64	4.64	4.64	4.65		4.68	4.68	4.68	4.69	
Surrey	4.66	4.67	4.68	4.66	4.66	4.67	4.68	4.69	4.67	4.67	4.65	4.67	4.68	4.66	4.66	4.70	4.71	4.72	4.70	4.70
Richmond	4.64	4.64	4.65	4.64		4.65	4.65	4.66	4.65		4.64	4.64	4.65	4.64		4.68	4.68	4.69	4.68	
Haney	4.66	4.66	4.66			4.67	4.67	4.67			4.67	4.66	4.66			4.70	4.70	4.70		
Coquitlam	4.65	4.65	4.66			4.66	4.66	4.67			4.65	4.66	4.66			4.69	4.69	4.70		
Forest Hills	4.64	4.65	4.65			4.65	4.66	4.66			4.64	4.65	4.65			4.68	4.69	4.69		
Prince George	5.18	5.39	5.39	5.39	5.39	5.19	5.40	5.40	5.40	5.40	5.18	5.39	5.40	5.39	5.39	5.22	5.43	5.43	5.43	5.43
Prince Rupert	5.70	5.77	5.77	5.90	5.90	5.71	5.78	5.78	5.91	5.91	5.70	5.78	5.78	5.90	5.90	5.74	5.81	5.81	5.94	5.94
Premium Intermodal Train Service: 73 hours.																				
INBOUND Drayage	Path 1					Path 2					Path 3					Path 4				
OUTBOUND Drayage	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Kelowna	4.03					4.04					4.03					4.07				
Kamloops																				
Burnaby	3.64	3.64	3.64	3.65		3.65	3.65	3.65	3.66		3.64	3.64	3.64	3.65		3.68	3.68	3.68	3.69	
Surrey	3.66	3.67	3.68	3.66	3.66	3.67	3.68	3.69	3.67	3.67	3.66	3.67	3.68	3.66	3.66	3.70	3.71	3.72	3.70	3.70
Richmond	3.64	3.64	3.65	3.64		3.65	3.65	3.66	3.65		3.64	3.64	3.65	3.64		3.68	3.68	3.69	3.68	
Haney	3.66	3.66	3.66			3.67	3.67	3.67			3.67	3.66	3.66			3.70	3.70	3.70		
Coquitlam	3.65	3.65	3.66			3.66	3.66	3.67			3.65	3.66	3.66			3.69	3.69	3.70		
Forest Hills	3.64	3.65	3.65			3.65	3.66	3.66			3.64	3.65	3.65			3.68	3.69	3.69		
Prince George																				
Prince Rupert																				

Table 2: Total Time (in Days) for shipments from Repentigny on the North Route

Table 2 provides the time elapsed (in number of days) since an order was released when shipments were moved along an intermodal chain formed by each of the two train service plus drayage at either ends. These times are the summation of travel times on different links and activity times at various sites. For visual and explanatory convenience the infeasible times have been shaded. For example, Path 1 for inbound drayage, R-IM service and Path 1 for outbound drayage from *Repentigny* to *Kelowna* takes 5.03 days, which is infeasible given the 5 day delivery time requirement of the receiver. Any infeasible route can be made feasible either by moving traffic between Montreal and Vancouver at a faster pace or by relaxing the delivery *"time"* specification. While the former can be done by employing faster trains, the latter is possible by penalizing late deliveries which any shipper would want to avoid as long as the faster train does not eat away the profit. Although Table 2 indicates that all shipments would arrive at their destinations before the cut-off time if P-IM is used, this expensive train service should be used to move only the shipments with destination in the greater Vancouver area. Morlok and Spasovic (1995) estimated \$0.70/mile as IM rail-haul cost, but in our case study it has been estimated as \$0.875/mile. Furthermore in the absence of any public information to quantify premium service a crude rule of thumb, namely the speed ratio between the two types of train services of 1.33, yielded \$1.164/mile as the rate for premium service.

The risk stemming from these services depends on the makeup of trains, and will be analyzed in the next section.

The third link of the intermodal chain i.e., outbound drayage, will trigger the reverse of the operations performed on the first link. It should be noted from Tables 2 and 3 that the driver will take any path except Path 1 for outbound drayage to the first receiver at *Kelowna*. This is because this path is not just the longest but also infeasible when used in conjunction with R-IM, but the infeasibility can be overcome by taking the more expensive P-IM. On reaching the receiver's location, the containers (trailers) are unloaded and the driver returns the truck to the pool.

Paths	*1*	*2*	*3*	*4*	*5*
Time(hrs.)	*21.30*	*18.38*	*18.35*	*18.40*	*18.50*
Distance (kms.)	*852*	*735*	*734*	*736*	*740*
Cost ($)	*1215*	*1068*	*1068*	*1070*	*1075*
Population Exposure (people)	*37*	*87*	*86*	*88*	*89*

Table 3: Per Container Outbound Drayage to *Kelowna*

From Table 3 it is clear that Path 1 may be the most expensive but it is also the safest amongst the five. The other four paths, while being very similar to each other from both cost and risk standpoint, expose roughly 2.5 times more than if Path 1 is used to move the hazardous cargo. By spending an extra $149 per container 49 fewer people per container will be exposed by taking Path 3. Finally roughly 1,700 more people will be exposed at the receiver's site, due to the handling of the hazardous containers from all ten shippers.

5. Analysis of the Trade-offs

In this section, we will discuss the routing options for intermodal shipments within the context of the *"time"* driven cost-risk trade-off. Note that there are two time-based constraints that define feasibility: the departure time of the intermodal train and the total delivery time. Since the population exposure at the shipper, receiver and IMRT locations are fixed, we will focus on mitigating transport risk via routing decisions at each leg of the intermodal journey. Figure 6 depicts the process of IM as well as the associated timeline among a shipper-receiver pair. The durations denoted by "flexible time" represents those activities for which a cost-risk trade-off can be made without violating time-feasibility. More specifically, any

transport activity in a flexible time window can be expedited (e.g., the use of P-IM rather than R-IM) to allow for more time for a following (or preceding) transport activity, which will enable the use of a path with less population exposure. The discussion below explains this interaction between cost, risk and time in IM of hazmats in the context of the case data provided in section 3.

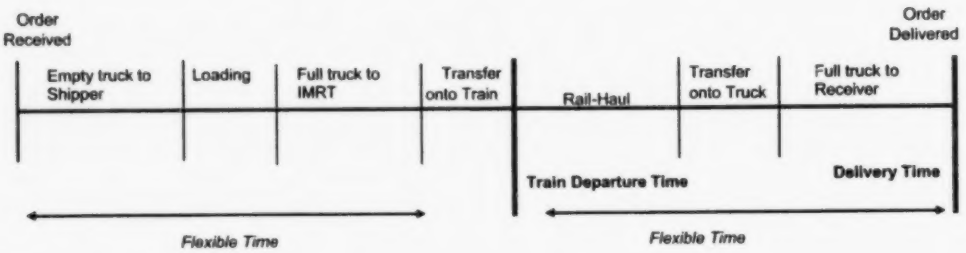

Figure 6: The Receivers and Delta Port Intermodal Yard

In Table 1 Path 1 would be taken by the driver, which is the cost-effective path as long as non-hazardous containers are being moved. But the judiciousness of this approach is undermined when hazardous cargo is involved, since we note from the same table that the shortest paths are not necessarily the least risky as they pass through the densest population centers. On the other hand we noticed that the longest paths to shippers in *Saint Hubert, Chateauguay, Beaconsfield, Kirkland, Saint Eustache* and *Sainte Therese*, are also the riskiest. Hence cost and risk may or may not be in conflict with each other, and using either cost or risk as the decision criterion may yield suboptimal results. For our case study both *cost* and *risk* will be used, and a *weighted* shortest path strategy that will also incorporate the element of *"time"* will be developed. The two primary stakeholders, namely regulatory agencies and IM parties, can arrive at mutually agreeable weights for cost and risk.

Table 4 focuses on the shippers at *Repentigny* and *Beaconsfield* in presenting the impact of different weighting schemes that incorporate cost and risk in a single attribute. The first scheme assumes cost and risk have unit weight i.e. a straightforward summation of cost and risk attributes of the shipment. In the next two schemes the cost figures are calibrated with the exposure figures as follows. Let C_p denote the cost and R_p denote the risk of path p, for all paths between a shipper and the IMRT. If $\overline{C}_{\max} = \max_p C_p$ and

$\overline{R}_{\max} = \max_p R_p$, then the calibration factor $\overline{C}_p = \frac{\overline{R}_{\max}}{\overline{C}_{\max}}$ is multiplied with cost and the result is added to path risk to generate the second scheme. Similarly, if $\tilde{C}_{\min} = \min_p C_p$ and $\tilde{R}_{\min} = \min_p R_p$ then the calibration factor $\tilde{C} = \frac{\tilde{R}_{\min}}{\tilde{C}_{\min}}$ is used to generate the third scheme. Calibration factors for the two schemes are 10.79 and 2.89, respectively. For the shipper at *Repentigny*, the best choice under each of the three scenarios is the same i.e., to use Path 4 for hazardous shipments. On the other hand the result under each scenario for the shipper at *Beanconsfield* is different, which warrants additional weight analysis based on stakeholder preferences. It is interesting to note that none of the routes chosen from the analysis above for the two shippers would have been identified by a pure cost-based approach. Through the complete evaluation, we found out that such a coincidence exists only for the shipper at *Saint Therese*.

Weighted Inbound Drayage for Repentigny				
Measure/ Paths	**1**	**2**	**3**	**4**
First Scheme	*3213*	*3051*	*2813*	***1566***
Second Scheme	*5700*	*5636*	*5319*	***4503***
Third Scheme	*3692*	*3549*	*3296*	***2132***

Weighted Inbound Drayage for Beaconsfield					
Measure/ Paths	**1**	**2**	**3**	**4**	**5**
First Scheme	*1309*	***1097***	*1105*	*1545*	*1592*
Second Scheme	***3458***	*3772*	*3729*	*4336*	*4412*
Third Scheme	*1723*	*1613*	***1611***	*2083*	*2135*

Table 4: Weighted Paths for Inbound Drayage

For the rail-haul link, we recollect that none of the path-combinations using R-IM was feasible for receivers at *Burnaby, Surrey, Richmond, Haney, Coquitlam* and *Forest Hills*. Hence these are the clear cases in which P-IM, albeit at a higher shipping cost, would have to be employed. Out of the 1036 containers to be moved west, 612 destined to these six centers would be moved on premium train service at the rate of $3,399, while the remaining 424 will take R-IM at a cost of $2,555 each. Now to compute the population exposure risk, one needs to know the exact number of hazardous containers traveling together on an intermodal train (Verma and Verter, 2005; Verma et al., 2005).

Of the 424 containers loaded on R-IM and destined to receivers outside greater Vancouver area, 219 have hazardous cargo. On the other hand P-IM has to move 612 containers, of which 319 have hazardous content. Although the length of the train can be varied, it is assumed that 120 containers (IMU) originating at Lachine Yard and destined for Vancouver can be accommodated on R-IM, while the rest are made available to Edmonton traffic. To reiterate it is assumed that the IM service provider has the capacity and equipment to move shipments as per demand, and hence these containers (trailers) will not be stranded at the yards waiting to be westbound. Although by assumption each shipment will arrive at the destination on schedule, the makeup of each IM train has to be ascertained in order to calculate the population exposure risk due to that train. Intuitively it would seem that population exposure risk should stem from moving 538 containers of hazardous cargo, which is correct but it would be fallacious to determine exposure risk based on this number alone (Verma and Verter, 2005), (Verma et al., 2005). What is the exposure risk stemming from each IM train?

	TRAIN:			
Assignment (Make-up)	Number (Type)	Length	# of hazmat containers	Population Exposure
First Plan:	*Train 1*	*119*	*59*	*328*
	Train 2	*118*	*65*	*350*
	Train 3	*100*	*45*	*280*
	Train 4	*87*	*50*	*300*
Second Plan:	*Train 1*	*119*	*59*	*328*
	Train 2	*118*	*65*	*350*
	Train 3	*100*	*45*	*280*
	Train 4	*87*	*50*	*300*
Third Plan:	*Hazmat Train #1*	*99*	*99*	*460*
	Hazmat Train #2	*120*	*120*	*501*
	Train 3	*104*		
	Train 4	*101*		

Table 5: Three Representative train assignments

The assignment of containers to each train will determine this. A heuristic whereby as far as possible the entire block of traffic from a particular shipper will be assigned to only one train could be used. *First plan* in Table 5 exhibits train make up based on such a heuristic. On the other hand since all the trains are arriving in Vancouver around the same time, an alternate train makeup could involve splitting consignment from one shipper. *Second plan* depicts this assignment, where only the non-hazardous cargoes have been

moved between trains compared to the first plan, which would mean same population exposure risk for the two plans. The evacuation distance was computed using the methodology developed in Verma and Verter (2005), and they are 4.36, 4.71, 3.62 and 3.89 miles, whereas a total of 1,258 people are exposed[1] under each plan. The *third plan*, motivated by Verma and Verter (2005), is to form an IM train on the lines of a *unit-train*. Specifically there would be two types of R-IM, characterized by the type of freight being hauled. Hazmat Trains # 1 and #2 will almost exclusively carry hazardous cargo, while the other two will carry non-hazardous containers. The threshold distances for the two hazmat unit-trains are 6.68 and 7.33 miles, and the two together will expose 961 persons. The usage of hazmat unit-train reduces the exposure by roughly 24%. It should be noted that the cost of operating IM services under each of the three plans is the same, and hence it makes sense to implement a load-assignment strategy that can bring down population exposure *risk*. We have seen in Verma and Verter (2005) and in Verma et al. (2005) that when hazardous cargo, with airborne characteristics travel together, they yield *economies of risk* due to non-linear nature of the resulting concentration curves.

Now 612 containers need to be moved by P-IM including 319 with hazardous cargo and once again any assignment heuristic can be used to load these trains. Since there is no Edmonton traffic, roughly 5 trains carrying 130-140 containers each will be required. The number of containers a train can carry is a parameter, and could be adjusted for a particular context. Given the possibility of substantial reduction in risk, it makes sense to divide traffic into hazardous and non-hazardous cargo and form unit-trains. There will be two hazmat unit-trains, one mixed train with 70 hazardous and 13 non-hazardous containers, and finally two regular freight trains moving non-hazardous containers. It should be noted that the mixed train has enough room to accommodate additional containers, and possibly move something from R-IM. Although moving anything from regular service to premium service is unlikely because of the cost involved, but then it is not impossible. Such decisions are made by the IM operator and would be based on marginal cost–benefit analysis. The threshold distances for the two hazmat and one mixed trains are 7.28, 7.67 and 4.91 miles, respectively, while the corresponding population exposures are 498, 522 and 365

[1] Unfortunately, we only have access to province-level data for British Columbia in contrast with the census sub-division data in Quebec. Since the total population of B.C. is assumed to be uniformly distributed to the entire province, the resulting population density in our data set significantly underestimates the actual density in Vancouver.

people respectively. The total population exposure from P-IM is 1,385 people. Hence a total of nine trains will have to be employed to move the shipments to Vancouver, and in that process $3,163,508 will be spent and 2,346 people would be exposed.

On reaching Vancouver, the containers are transferred to the waiting trucks to start the last leg of their journey, viz. outbound drayage. We recollect that, given the train service used to reach Vancouver, some paths are infeasible. For example, path 1 to *Kelowna* is infeasible given that the load destined for *Kelowna* from all shippers have arrived on R-IM. It is evident from Table 3 that this is the longest path from Vancouver to *Kelowna*, and hence the driver wouldn't take this path. On the basis of cost alone Path 3 is the cheapest, but once again population exposure risk needs to be incorporated into decision making.

Weighted Outbound Drayage to Kelowna					
Measure/ Paths	**1**	**2**	**3**	**4**	**5**
First Scheme	*1102*	*1005*	***1004***	*1008*	*1014*
Second Scheme	***1219***	*1280*	*1275*	*1285*	*1295*
Third Scheme	*1140*	*1095*	***1093***	*1099*	*1106*

Weighted Oubound Drayage to Burnaby				
Measure/ Paths	**1**	**2**	**3**	**4**
First Scheme	***480***	*567*	*535*	*670*
Second Scheme	***1888***	*2232*	*2106*	*2639*
Third Scheme	***941***	*1112*	*1050*	*1315*

Table 6: Weighted Paths for Outbound Drayage

According to weight based results in Table 6, two of the three paths to *Kelowna* match the shortest path in Table 3. Both these paths expose 2.5 times more people than Path 1, which has the least exposure but is the longest. Clearly Path 1 can be taken only if P-IM is used to move shipments to Vancouver, while the other four paths can be taken irrespective of the train service. For this receiver while two of the three recommendations are in line with a pure cost minimization objective, the third is consistent with risk minimization objective, and clearly appropriate weights for the two objectives have to be decided by the stakeholders. On the other hand decision about shipments to *Burnaby* is quite trivial, since it is one of the few instances where minimum cost and risk are on the same path.

Until now shipments to *Kelowna* from each of the ten shippers are moved to Vancouver by R-IM, and that was dictated by cost considerations. Now let us assume that all the hazardous containers to *Kelowna*

are moved by the P-IM, thereby reaching *Vancouver* yard in roughly 4.2 days. Given that now the truck drivers have more time before the 5 day cut-off period, they can take Path 1 which although being a little bit more expensive has the least population exposure. Population exposure risk can be reduced by 57% by spending an extra $147 per container, and the total risk stemming from shipments to Kelowna can be reduced by roughly 2,600 people by spending approximately $8,000 more. The 53 containers with hazardous cargo destined for this receiver can be accommodated on the mixed P-IM, which will make it the third hazmat train, while the 13 containers with non-hazardous cargo on this train can be moved to the two regular trains.

The number of containers with hazardous cargo on R-IM will be reduced by a corresponding amount. Now between the two hazmat unit-trains there is an opening for 53 additional containers, due to the transfer of the ones with hazardous cargo destined for Kelowna to P-IM. These new assignments will eliminate the need to form and run the fourth train, although the third train will have 21 extra containers. Normally the IM operator should be able to accommodate the 21 extra containers in the same train, but if not these containers can always be loaded on to first P-IM hazmat train, which has 22 open slots. Normally such an assignment could be an expensive proposition to the IM operator, but then it eliminates the need to run a fourth train. On the other hand a shipper will have no problem with this revised loading since the load is reaching Vancouver well before the scheduled time, but normally such a revision will be done without the knowledge of the shipper, who is only concerned about the safe and timely delivery of the shipments. In addition, shippers have no say in the assignments/loading of IM trains, which is the exclusive domain of the IM operators.

The analysis till this point was based on the assumption that there is only one intermodal route between Montreal and Vancover, but now we want to evaluate the impact of introducing another route between these two cities. Suppose there is another set of train services running on the *South* route in Figure 4. The trains on this route have the same characteristics as the ones on the *North* route, except that it goes through Calgary, and departs from Lachine yard two hours later than the one through Edmonton. The length of *South* route as measured in *ArcView GIS* is 2,713 miles, which is a full 207 miles shorter than the *North*

Route. The R-IM will cover the yard to yard distance in 96 hours, including the 6 hour for container swap at Calgary. On the other hand, a P-IM through the *South Route* will have a 68 hour yard to yard run time. Given the original delivery times and the length of this route all the intermodal combinations are feasible, which implies that all demands can be met on time using R-IM and hence there is no need employ P-IM to move any traffic.

Given that *South* route is shorter than the *North* route one would expect entire traffic on the former, but that may not happen since the IM operator may have to split traffic between the two routes due to the nature of the demand. Normally a shipper will approach an IM operator (railroad operator) with the delivery date and service type preferences, and based on the delivery date the IM operator will quote a price and the time of delivery. The shippers are only interested in the timely and safe arrival of their shipments, without worrying about the route a shipment may take. According to Nozick and Morlok (1997), as soon as a container leaves a shipper's location, almost simultaneously information regarding the destination and content (if hazardous) of the shipment is generated. So in essence a route plan has been prepared for the shipment, without the knowledge of the shipper, even before the shipment reaches the IM yard. The terminal to terminal routes of these IM trains are fixed, and could safely be assumed to be the shortest. In other words, an IM operator knows that if an R-IM on *South* route can enable meeting demands on time, then there is very little motivation to use R-IM on *North* route. But an IM operator could route traffic over the longer *North* route if there is a less-than-train load traffic for Edmonton and something needs to be moved from Edmonton to Vancouver. Of course only the shipments with enough buffer time would be consolidated with the Edmonton traffic and dispatched on *North* route.

As far as cost goes, the IM operator will not quote two different costs for the R-IM on two routes. It is so because the shorter route will always be preferred by the shippers, and it will also be less expensive. Hence, irrespective of the routes, the IM operator will quote only two rates, one for *regular* and the other for *premium* service. We have already qualified that almost always there will be only one route, but in instances with multiple routes one would expect the quotes to be based on the longest route. Although the quotes will be based on the longest route, but the option to ship traffic destined for areas in and around

Vancouver (*Burnaby, Surrey, Richmond, Haney, Coquitlam* and *Forest Hills*) is no longer limited to P-IM on the *North* route. Now the shippers have the option to use R-IM on the *South* route and still make it to the receiver by the specified "*time*". So moving 1036 containers (trailers) on R-IM on this route will cost $ 2,646,980, which is $ 516,600 lower when *North* route was being used to move shipments. The rail-haul cost savings indicated above is possible only when the cost structure and routes are transparent to each and every player in the system, which is never the case and hence one should not read too much into the cost savings.

Now given that this new route is being taken, what will be the impact on *population exposure*? As alluded to above, none of the shipment needs to be connected to P-IM on this route. All the containers irrespective of the nature of the cargo will travel on R-IM, and since the arrival of all the trains is assumed to be back-to-back in Vancouver, one can resort to a simple loading of traffic in the Lachine yard without worrying about any delay. Four hazmat unit-trains, one mixed train, and four regular freight trains would be formed to move on the *South* route. Each of the four hazmat trains will carry 120 hazardous containers thereby exposing 548 people each, while the mixed train has 58 hazardous containers and will expose 358 people. The population exposure on the *South* route is 2,550 people, while 2,340 people were exposed on the *North* route. It appears that the route through Calgary passes through denser population centers than the route through Edmonton and bypassing Calgary.

Roughly speaking the IM operator can save a combined total of $516,600 by taking this *South* route, but now 210 more persons are being exposed. This train leaves two-hours later than the one taking the *North* route, which translates into more time for inbound drayage, specifically the cut-off time for the shippers. Now the shippers have more time, and if the containers have been loaded, then the extra time could be used to route the loaded truck via a weighted minimum path rather than the conventional least costly one. On the outbound drayage end, it was noticed in Tables 3 and 6 that Path 1 to *Kelowna* was infeasible when used in conjunction with R-IM on the *North* route. But if R-IM on the *South* route is being used, this is a feasible path. Moreover this path has the least risk, and hence presents a good possibility of being taken if risk consideration outweighs cost concerns. It is worth reiterating that specified-time or service level as

demanded by the receivers dictates the paths and train service to be taken in order to adhere to the specifications. If the specified-time allows some flexibility, a longer but less risky route can be taken for drayage purposes. In general, risk reduction is possible only when all the IM parties are concerned about safety and not driven just by the desire to minimize cost.

To sum up, the introduction of *South* route between Montreal and Vancouver increases the number of options for the IM operator. Although it is shorter, it is riskier due to higher population density around the Calgary sector. While on the one hand this route eliminates the need to use P-IM, it provides additional time for both inbound and outbound drayage on the other. This additional time opens up the option to take routes, which although a little longer are less risky.

6. Conclusion

This work was motivated by the need to develop a solid understating of the trade-offs in IM, which combine the advantages of rail and truck transportation of hazmats. A realistic case study was used to illustrate an intelligent enumeration technique to solve a 100 supply-demand pair problem, and demonstrate societal risk reduction given flexibility in specified-time. It is possible to reduce population exposure risk by spending more money and/or readying the shipments at an earlier time in the event of inbound drayage, and by taking the faster service for the rail-haul in order to enable the outbound drayage to take the best possible risk-cost weighted path to the receiver's site. In addition, population exposure stemming from intermodal trains can be reduced by implementing a train make-up scheme striving for hazmat unit-trains. In general, risk reduction is possible only when all the IM parties are concerned about safety and not driven just by the desire to minimize cost.

Our immediate future research direction is the development of a mathematical formulation and a solution procedure for the general case of the problem studied in this paper, which involves multiple IMRT pairs. Other directions for future research include, studying congestion in the IM system by relaxing the just-in-time assumption; comparing the performance of intermodal transportation with rail and road shipments from a risk-cost perspective; and investigating the assignment of intermodal units to flat railcars and make-

up of intermodal train services when hazardous cargo is involved. Perhaps more importantly analyzing the suitability of the assessment scheme proposed in this paper to other forms of intermodal transportation constitutes a fruitful avenue.

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